Gadgets and Trinkets, The Upstream Linux Way

Embedded Linux Conference Europe 2020

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GLIDER bv

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Table of Contents

About Me (and Linux)

- **Freelance Embedded Linux Kernel Hacker**
- Started with Linux as a hobbyist
- Amiga, PPC, FBDev, MIPS, PS3/Cell, ...

- **Maintainer of the m68k architecture**
  since 2004

- **Maintainer of Renesas clock and pin control drivers**
  since 2016
- **Maintainer of Renesas ARM SoC platforms**
  since July 2019

Connecting Simple Devices to a Linux System

- Sensors, motors, switches, LEDs, actuators, displays, solenoids, ...
- **Makers** and **Industrial Automation**

Images © SIMAC Electronics GmbH, Olimex Ltd

Arduino

- Platform of choice for hooking up simple devices
- Large ecosystem
- Multiple hardware platforms (Various Arduinos, ESP32, Teensy, . . .)
- Lots of libraries, supporting most popular devices
- Limited processing power
- No hardware description, devices hardcoded in software
- Some common support across boards/families (pin 13 = LED)

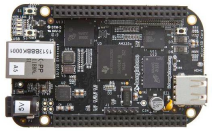
Arduino
APIs

- **Pins**
  - `pinMode()`
  - `digitalRead()` / `digitalWrite()`
  - `analogRead()` / `analogWrite()`
- **Buses**
  - `Wire` (i2c)
  - `SPI`
  - `Serial`
  - `OneWire`
- **Devices**
  - `DallasTemperature`
  - `...`

Linux

- Platform of choice for devices with a *real* OS and connectivity
- Large ecosystem
- Lots of drivers supporting most popular devices
- More processing power
  - Ranging from single-core systems with 1 MiB RAM to supercomputers
- Hardware description:
  - Discoverable devices (PCI, . . .)
  - Devices described by firmware (ACPI, real Open Firmware)
  - Flattened Device Tree
  - Board files ⇒ FDT

Linux
APIs

- Strict separation of kernel and userspace
  - (most) Drivers in kernelspace
  - Application in userspace
  - Standardized APIs
- Platform AND peripherals can be replaced without changing the application
  -  ⟷  ⟷ 
  - Swapping e.g. sensors

Example: Getting To Blinky
Arduino

```
void setup()
{
    pinMode(LED_BUILTIN, OUTPUT);
}

void loop()
{
    digitalWrite(LED_BUILTIN, HIGH);
    delay(1000);
    digitalWrite(LED_BUILTIN, LOW);
    delay(1000);
}
```

Can we do the same on Linux? From userspace?

Example: Getting To Blinky
Linux / sysfs GPIO

```
# echo 953 > /sys/class/gpio/export
# echo out > /sys/class/gpio/gpio953/direction
# echo 1 > /sys/class/gpio/gpio953/value
# echo 0 > /sys/class/gpio/gpio953/value
# echo high > /sys/class/gpio/gpio953/direction # shorthand for out/1
# echo low > /sys/class/gpio/gpio953/direction  # shorthand for out/0
```

- How to know the GPIO number? Can it change?
- sysfs GPIO is deprecated!
- Arduino-alike libs (for C, Shell, Python, . . .)

Example: Getting To Blinky
Linux / chardev GPIO / libgpiod

```
# gpiodetect
gpiochip0 [e6050000.gpio] (16 lines)
...
gpiochip8 [4-0020] (8 lines)
gpiochip9 [bd9571mwv-gpio] (2 lines)
# gpioinfo
gpiochip0 - 16 lines:
        line   0:      unnamed       unused   input  active-high
        line   1:      unnamed       unused   input  active-high
        line   2:      unnamed "SDHI0 VccQ"  output  active-high [used]
...

# gpioset gpiochip2 19=0                  # LED off
# gpioset gpiochip2 19=1                  # blinks very briefly?!?
# gpioset -m time -u 500000 gpiochip2 19=1
# gpioset -m wait gpiochip2 19=0 20=1 21=0 # multiple
```

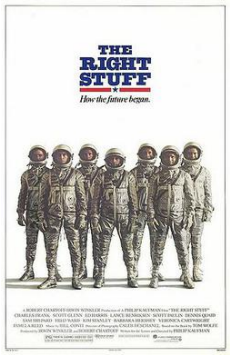
Example: Getting To Blinky
Linux / sysfs LED

```
# echo 0 > /sys/class/leds/led6/brightness
# echo 1 > /sys/class/leds/led6/brightness

# cat /sys/class/leds/led6/trigger
[none] usbport timer oneshot disk-activity disk-read disk-write ide-disk m
# echo activity > /sys/class/leds/led6/trigger

# echo pattern > /sys/class/leds/led6/trigger
# echo 0 500 255 500 > /sys/class/leds/led6/pattern           # PWM
# echo 0 500 0 0 255 500 255 0 > /sys/class/leds/led6/pattern # Binary
```

- Kernel drivers to the rescue
- Needs hardware description

Linux
The Right Stuff

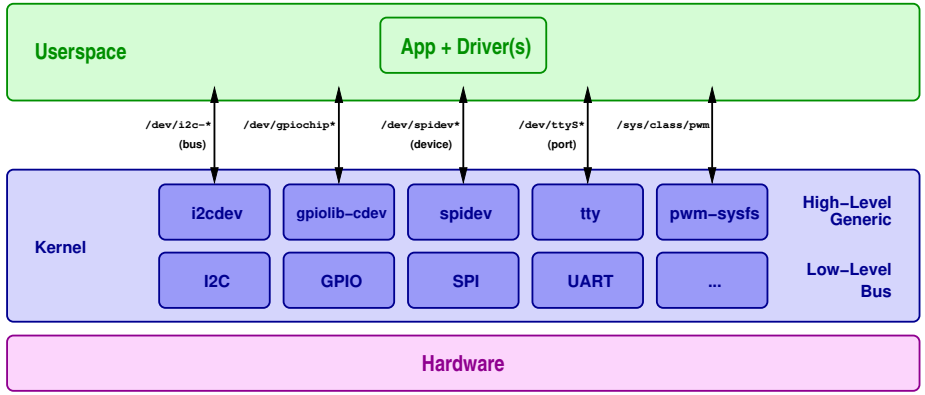
- **Out-of-Tree Linux**
  - Do whatever you want
  - Custom solutions
  - Less sharing
- **Upstream Linux**
  - More sharing
  - Long Term vision and maintenance
  - Work with the community to get your work accepted
  - Follow the (un)written/. . . rules



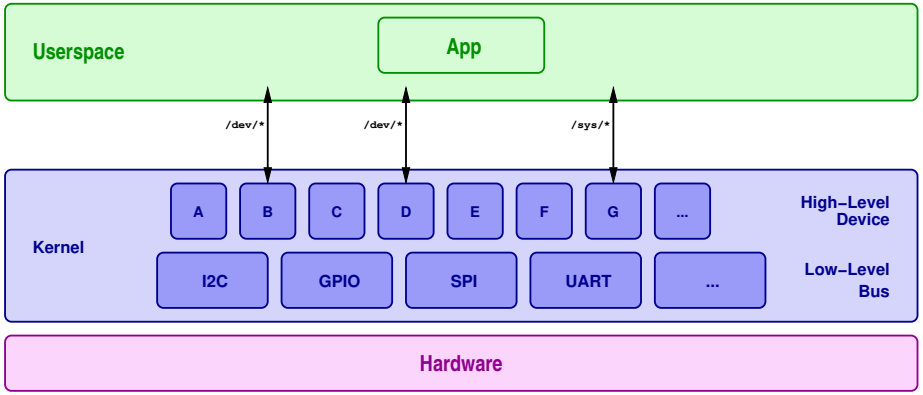
There's only one way of Linux, and that's upstream, upstream, upstream!!!

Image © Warner Bros. Entertainment Inc.

Userspace Drivers



Kernelspace Drivers



Comparison: Userspace vs. Kernelspace Drivers

Userspace Drivers

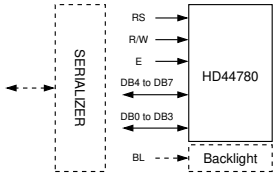
- ✓ Simpler to get something to work
- ✓ Licensing
- ✓ Custom microcontroller protocols
- X Reuse and sharing
- X Interrupts
- X Overhead

Kernelspace Drivers

- ✓ Efficiency
- ✓ Reuse
- ✓ Abstraction (replace hardware, keep interface)
- ✓ Integration with other subsystems
- ✓ Interrupts
- X More complex
- X Upstreaming effort

Too many userspace drivers in these Arduino/<Fruit>Pi/96boards/. . . days

Example: HD44780 Character LCD



Userspace: 5+ drivers/libs

1. GPIO (4-bit/8-bit)
2. I2C
3. SPI
4. W1
5. Custom microcontroller protocol

Kernelspace: One "new" driver

1. Panel driver → GPIO

\+ I2C/SPI/W1 I/O Expander drivers

\+ Custom frontend?

Existing Drivers

- Input (`evdev`, `/dev/input/event*`)
  - gpio-keys(-polled)
  - gpio-matrix-keypad ⇔ `https://maker.pro/raspberry-pi/tutorial/how-to-use-a-keypad-with-a-raspberry-pi-4`
  - rotary-encoder
  - touchscreen
- Output
  - gpio-leds
  - pwm-leds
  - Various displays
- Bit-banged bus implementations
  - i2c-gpio
  - spi_gpio
  - w1-gpio

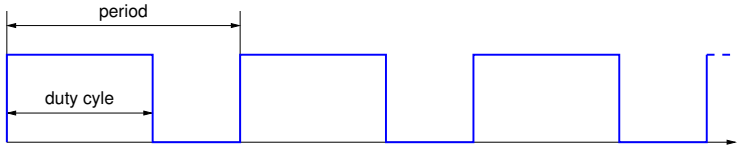
Industrial IO (IIO)

- Sensors, ADC, DAC, . . .
- Mostly I2C/SPI
- sysfs / libiio

LibIIO — A Library for Interfacing with Linux IIO Devices
Tuesday, 17h15 GMT

```
$ iio_info -n h3-salvator-xs
Library version: 0.10 (git tag: v0.10)
Compiled with backends: local xml ip usb serial
IIO context created with network backend.
...
IIO context has 2 devices:
        iio:device0: max9611
                5 channels found:
                        current:  (input)
                        2 channel-specific attributes found:
                                attr  0: input value: 2214.500000000
                                attr  1: shunt_resistor value: 0.005000
                        power:  (input)
                        2 channel-specific attributes found:
                                attr  0: input value: 1854.375600000
                                attr  1: shunt_resistor value: 0.005000
                        temp:  (input)
                        2 channel-specific attributes found:
                                attr  0: raw value: 75
                                attr  1: scale value: 480.076812289
                        voltage0:  (input)
                        1 channel-specific attributes found:
                                attr  0: input value: 10.857500000
                        voltage1:  (input)
```


Pulse-Width Modulation (PWM)



- pwm-leds
- PWM in-kernel mostly for display backlight
- Userspace: sysfs `/sys/class/pwm/` (cfr. legacy GPIO)

```
$ echo 0 > /sys/class/pwm/pwmchip0/export
$ echo 50000 > /sys/class/pwm/pwmchip0/pwm0/period      # in ns
$ echo 30000 > /sys/class/pwm/pwmchip0/pwm0/duty_cycle # in ns
$ echo 1 > /sys/class/pwm/pwmchip0/pwm0/enable
```

- No chardev uAPI or `libpwmd` yet

RGB LEDs?

It's complicated...

- **Multicolor Framework v30**
  `https://lwn.net/Articles/826046/`
- v31 made it into v5.9-rc1!
- Control global/local brightness of a string of LEDs

  ⇒ RGB LEDs need more

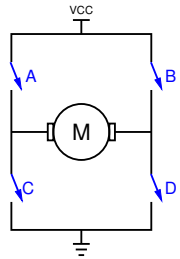
- NeoPixels (WS2812) and DotStars (APA102) etc?
  - NeoPixels: precise timing, SPI abuse?
  - Upstream?

Image © BillT3

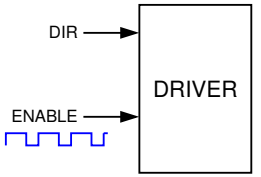
Motors & Actuators?

- No gpio-motors
- No gpio-relays
- No gpio-actuators

  Workaround/abuse: gpio-leds



- Motor Control / H-Bridge
- Generic H-Bridge driver?
  (forward/backward/stop/brake, speed)



GPIO Aggregator (v5.8+)

- GPIO access control uses permissions on `/dev/gpiochip*`
  ⇒ All or Nothing
- **Solution:** Aggregate existing GPIOs, and expose them as a new gpiochip

```
# echo 'e6052000.gpio 19 e6050000.gpio 20-21' > \
      /sys/bus/platform/drivers/gpio-aggregator/new_device
# gpioinfo gpio-aggregator.0
gpiochip12 - 3 lines:
        line   0:      unnamed       unused   input  active-high
        line   1:      unnamed       unused   input  active-high
        line   2:      unnamed       unused   input  active-high
# chown geert /dev/gpiochip12
```

- Started as a way to group GPIOs for export to a VM
- Generic GPIO Driver (cfr. i2cdev/spidev)

Hardware Description

Tell Linux what devices are present

- PCI, W1: Autoprobe
- I2C: Can be manual for simple devices:

```
# echo pcf8574 0x24 > /sys/bus/i2c/devices/i2c-1/new_device
```

- `/dev/i2c-%u`, `/dev/ttyS%u`: Always available
- Devices described in Device Tree
  - Identification through `compatible` values
  - Resources: `reg`, `interrupts`
  - Properties (may be device-specific)
  - Phandles
  - Subnodes

Sample Device Tree Snippet: SPI Controller and Device

```
spi1: spi@e6e10000 {
        compatible = "renesas,msiof-r8a7791", "renesas,rcar-gen2-msiof";
        reg = <0 0xe6e10000 0 0x0064>;
        interrupts = <GIC_SPI 157 IRQ_TYPE_LEVEL_HIGH>;
        clocks = <&cpg CPG_MOD 208>;
        #address-cells = <1>;
        #size-cells = <0>;
        status = "disabled";
};

&spi1 {
        status = "okay";

        flash0: eeprom@0 {
                compatible = "microchip,25lc040", "atmel,at25";
                reg = <0>;
                pagesize = <16>;
                size = <512>;
                address-width = <9>;
                spi-max-frequency = <100000>;
        };
};
```

"I need spidev in DT!"

```
&spi1 {
        status = "okay";

        spidev@0 {
                compatible = "spidev";
                reg = <0>;
                spi-max-frequency = <100000>;
        };
};
```

Rule #1: DT describes hardware, not software policy

- Use a proper compatible value!
- Add to `drivers/spi/spidev.c:spidev_dt_ids[]`
- Or bind manually:

```
# echo spidev > /sys/class/spi_master/spi1/spi1.0/driver_override
# echo spi1.0 > /sys/bus/spi/drivers/spidev/bind
```

and `/dev/spidev1.0` appears

Enabling My Device in DT

`myvendor,mydevice`

1. Add DT bindings (preferably json-schema / YAML)
   - Vendor prefix
     `Documentation/devicetree/bindings/vendor-prefixes.yaml`
   - Device DT bindings
     `Documentation/devicetree/bindings/.../myvendor,mydevice.yaml`
   - Or trivial device
     `Documentation/devicetree/bindings/trivial-devices.yaml`
2. Driver
3. Device node in board DTS
4. Validate

```
$ make dt_binding_check dtbs_check \
          DT_SCHEMA_FILES=.../myvendor,mydevice.yaml
```

DT Bindings Example: GPIO-operated Door

```
# SPDX-License-Identifier: (GPL-2.0-only OR BSD-2-Clause)
%YAML 1.2
---
$id: "http://devicetree.org/schemas/misc/myvendor,mydoor.yaml#"
$schema: "http://devicetree.org/meta-schemas/core.yaml#"

title: Myvendor mydoor device

maintainers:
  - J.K. Hacker <developer@myvendor.com>

properties:
  compatible:
    const: myvendor,mydoor

  gpios:
    maxItems: 2

  gpio-line-names:
    items:
      - const: "open"
      - const: "lock"

required:
  - compatible
  - gpios
  - gpio-line-names

additionalProperties: false
```

```
examples:
  - |
    #include <dt-bindings/gpio/gpio.h>
    door {
            compatible = "myvendor,mydoor";

            gpios = <&gpio2 19 GPIO_ACTIVE_HIGH>,
                    <&gpio2 20 GPIO_ACTIVE_LOW>;
            gpio-line-names = "open", "lock";
    };
```

Disclaimer: example fails to validate!

Driver / Binding

- New driver / existing driver
- Add compatible value to driver
- Or bind manually:

```
# echo gpio-aggregator > /sys/bus/platform/devices/door/driver_override
# echo door > /sys/bus/platform/drivers/gpio-aggregator/bind

# gpioinfo door
gpiochip12 - 2 lines:
        line   0:       "open"       unused   input  active-high
        line   1:       "lock"       unused   input  active-high

# gpiofind open
gpiochip12 0

# gpioinfo gpiochip12
gpiochip12 - 2 lines:
        line   0:       "open"       unused   input  active-high
        line   1:       "lock"       unused   input  active-high
```

How to get it in your DT?

1. Add to board DTS
2. Create a DT overlay (more flexibility)
   - 2.1 Load overlay at runtime ⇒ requires out-of-tree patches (I keep them up-to-date)
     `https://elinux.org/R-Car/DT-Overlays`
     `https://git.kernel.org/pub/scm/linux/kernel/git/geert/renesas-drivers.git/log/?h=topic/overlays`
   - 2.2 Let U-Boot load the overlay before starting the kernel
     `https://gitlab.denx.de/u-boot/u-boot/-/blob/master/doc/README.fdt-overlays`
     `https://gitlab.denx.de/u-boot/u-boot/-/blob/master/doc/uImage.FIT/overlay-fdt-boot.txt`
   - 2.3 Combine base DTS and overlays using `fdtoverlay`

Sample DT Overlay / Sugar Syntax

```
/dts-v1/;
/plugin/; // Main DTS must be processed with -@

&spi1 {
        #address-cells = <1>;
        #size-cells = <0>;
        status = "okay";

        flash0: eeprom@0 {
                compatible = "microchip,25lc040", "atmel,at25";
                reg = <0>;
                pagesize = <16>;
                size = <512>;
                address-width = <9>;
                spi-max-frequency = <100000>;
        };
};
```

Dynamic DT Overlays

- BeagleBone Black Cape Manager (Pantelis et al), used on Raspberry Pi, too
- What works (not)?
  - ✓ SPI, I2C, GPIO hogs, Platform devices (using `of_reconfig_notifier_register()`)
  - ✓ Pinctrl
  - ✓ Enable/disable device
  - X DT aliases
  - X Endpoints?
  - ...
- Caveats
  - Know what you're doing, **with great power comes great responsability!**
  - Memory leaks, locking, ...
  - *Frank's Evolving Overlay Thoughts*
    `https://elinux.org/Frank%27s_Evolving_Overlay_Thoughts`
- Do we really need this?
  - No hotplugging in real life, but useful for prototyping
  - FPGA hardware can be reconfigured at run-time
  - Arduino has dynamic pin configuration

Connector Framework: Making DT Overlays Safe(r)

- Confine overlays to a subset of the system:

  The Connector

- Candidates for a Proof-of-Concept?
  - Qwiic, Grove, UEXT, Pmod, mikroBUS, Feather Wing, Raspberry Pi HAT, BeagleBone Cape: 4–92 pins
  - Custom development board connectors: +100 pins
  - Various levels of functionality and multiplexing

- To Be Continued. . .

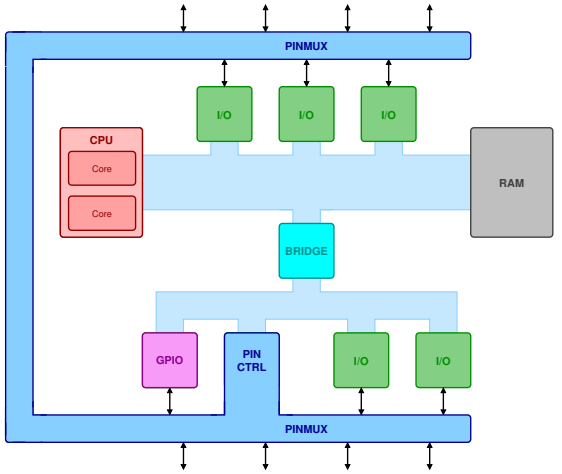
Thanks & Acknowledgements

- **Renesas Electronics Corporation**, for contracting me for upstream Linux kernel work,
- The **Linux Foundation**, for organizing this conference and giving me the opportunity to present here,
- The **Linux Kernel Community**, for having so much fun working together towards a common goal.

Questions & Answers

Appendix

Pin Control and Pin Muxing (pinctrl)



- Very SoC-specific
- Some common properties
- Requires DT (debugfs?)

Appendix
Pinctrl Examples

```
i2c0_pins: pinmux_i2c0_pins {
      pinctrl-single,pins = <
            AM33XX_PADCONF(AM335X_PIN_I2C0_SDA, PIN_INPUT_PULLUP, MUX_MODE0)
                        /* i2c0_sda.i2c0_sda */
            AM33XX_PADCONF(AM335X_PIN_I2C0_SCL, PIN_INPUT_PULLUP, MUX_MODE0)
                        /* i2c0_scl.i2c0_scl */
      >;
};

scif2_pins: serial2 {
        pinmux = <RZA1_PINMUX(3, 0, 6)>,        /* TxD2 */
                 <RZA1_PINMUX(3, 2, 4)>;        /* RxD2 */
};

ether_pins: ether {
        groups = "eth_link", "eth_mdio", "eth_rmii";
        function = "eth";
};
```

Appendix
Connectors

Name	Pins	Signals
Qwiic Connect System (SparkFun Electronics) https://www.sparkfun.com/qwiic	4	power + I2C
Grove Ecosystem (Seeed Studio) https://wiki.seeedstudio.com/Grove_System/	4	digital, analog, UART, or I2C
UEXT (Olimex) https://www.olimex.com/Products/Modules/UEXT/	10	UART + I2C + SPI
Pmod Interface (Digilent) https://reference.digilentinc.com/reference/pmod/start	6/12	GPIO, PWM, SPI, UART, I2C, I2S, H-Bridge, Interrupt, Reset
mikroBUS (MikroElektronika) https://www.mikroe.com/mikrobus	16	PWM + UART + I2C + SPI + Analog + Interrupt + Reset
Feather Wing (Adafruit) https://www.adafruit.com/feather	28	UART + I2C + SPI, Analog, PWM, GPIO
Raspberry Pi HAT https://github.com/raspberrypi/hats	(26)40	UART + I2C + SPI, PWM, GPIO
BeagleBone Cape https://beagleboard.org/capes	2 × 46	Heavily multiplexed

Appendix
References

- *Linux GPIO: Evolution and Current State of the User API*, Bartosz Golaszewski, Embedded Linux Conference 2020
  https://elinux.org/ELC_2020_Presentations
- linux/Documentation/ABI/testing/gpio-cdev
- linux/Documentation/ABI/testing/sysfs-class-pwm
- linux/Documentation/admin-guide/gpio/gpio-aggregator.rst
- linux/Documentation/devicetree/bindings/writing-bindings.rst
- linux/Documentation/driver-api/gpio/drivers-on-gpio.rst
- linux/Documentation/driver-api/gpio/using-gpio.rst
- linux/Documentation/i2c/dev-interface.rst
- linux/Documentation/spi/spidev.rst